Application for
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Of

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SEMICONDUCTOR LASER

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SEMICONDUCTOR LASER

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates to a semicon-
ductor laser and in particular, to a semiconductor

5   laser for communication that has a short resonator and
can favorably be used for high-speed modulation and
wide-range wavelength change operation, and an optical
module thereof.

Description of the Related Art

10   It is known theoretically and experimetally
that by reducing a resonator length of an end light
emitting type semiconductor laser down to 200
micrometers, it is possible to lower a threshold value
current flow and increase a mitigation oscillation

15   frequency. Fig. 1 shows a calculation example of
resonator-length-dependency of the laser threshold
value current, mitigation oscillation frequency, and
series resistance. A laser active layer is assumed to
have a lattice-distortion-based InGaAsP multi-quantum

20   well structure. From this figure, it is clear that the
short resonator is advantageous for lowering a
threshold value current and increase a mitigation
oscillation frequency. However, when the resonator
becomes shorter, the series resistance is remarkably

25   increased and accordingly, current application to the

laser is accompanied by Joule heat, thereby signifi-
cantly deteriorating the optical output characteristic.
For example, when the resonator has length of 100
micrometers, the series resistance reaches 20 ohms,

5 which is four times greater than the laser resonator of
400 micrometers that is normally used. From this view
point, as has been described above, the performance
improvement of the semiconductor laser by reducing the
resonator length can actually be realized only to 200

10 micrometers. On the other hand, it is known that in a
distribution reflection type laser, by reducing the
active area length, it is possible to obtain a stable
longitudinal mode and increase the wave length change-
able width. This is because a mode jump interval $\Delta\lambda$ of

15 the distribution reflection type laser and an active
area length L_a are in the relationship as follows: $\Delta\lambda = \lambda^2/2nL_a$, wherein n represents a refractive index of the
laser medium and λ represents an oscillation wave-
length. In this case also, when the resonator and the

20 active area are reduced so as to increase the $\Delta\lambda$, the
laser gain is lowered, and the electric resistance and
thermal resistance are increased. Accordingly,
although the aforementioned effect is reported, it
still cannot be used actually in practice. It should

25 be noted that this type of semiconductor laser is
described in the 17th Semiconductor Laser International
Conference, technical digest paper ThA4.

SUMMARY OF THE INVENTION

It is therefore an object of the present invention to provide a short-resonator laser capable of high-speed operation with a low threshold value current and an element structure which has an excellent wave-length stability and can be changed in wavelength, and a production method thereof. Especially, the present invention has an object to realize a short-resonator laser having a resonator length not greater than 200 micrometers. Another object of the present invention is to provide an optical module using these optical elements and capable of a high-performance operation at a low cost.

In order to achieve the aforementioned objects, we have devised an element structure in which a laser short oscillator waveguide is partially or entirely increased in lateral width allowing lateral multi-mode, thereby enhancing the laser gain and reducing the electric resistance and thermal resist-ance. Here, by using self-focusing effect as a result of multi-mode interference effect, it is possible to reduce the mode conversion loss in the laser resonator and the light intensity distribution at the laser emitting end becomes a single-hill lowest order mode. Thus, it is possible to obtain a structure appropriate for connection with an optical fiber. Because of the laser characteristic, in this structure, it is necessary to accurately set dimension of the waveguide

of the multi-mode interference waveguide portion and accordingly, the conventional cleave method having a large dimensional error cannot be used for forming the resonator. We have also devised a method for producing a laser oscillator including the multi-mode inter- ference waveguide with a high accuracy, by using the lithography technique and the dry etching technique in combination.

Other objects, features and advantages of the invention will become apparent from the following description of the embodiments of the invention taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a view for explaining effects of the present invention.

Fig. 2 is a view for explaining a first embodiment of the present invention.

Fig. 3 is a view for explaining a modified embodiment of the present invention.

Fig. 4 is a view for explaining effects of the present invention.

Fig. 5 is a view for explaining effects of the present invention.

Fig. 6 is a view for explaining a principle of the present invention.

Fig. 7A is a view for explaining a second embodiment of the present invention.

Fig. 7B is a cross-sectional view of Fig. 7A at AA'.

Fig. 8A is a view for explaining a wavelength tuning characteristic.

5   Fig. 8B is a view for explaining effects of the present invention.

Fig. 9A is a view for explaining a third embodiment of the present invention.

Fig. 9B is a cross-sectional view of Fig. 9A

10   at BB'.

Fig. 10 is a view for explaining a fourth embodiment of the present invention.

Fig. 11 is a view for explaining effects of a laser resonator length with respect to laser character-

15   istics.

DETAILED DESCRIPTION OF THE EMBODIMENTS

Description will now be directed to embodiments of the present invent ion with reference to Fig. 1 to Fig. 9.

20   [Embodiment 1]

Fig. 1 shows an example of semiconductor laser according to the present invention having a wavelength of 1.3-micrometer band capable of high-speed modulation not smaller than 40 giga bits per second.

25   As shown in Fig. 1, on an n-type (100)InP semiconductor substrate 101 are successively formed by the organic metal gaseous phase growth method: an n-type InP

buffer layer 102 having a thickness of 1.0 micrometers;
an n-type InAlAs buffer layer 103 having a thickness of
0.5 micrometers; an n-type InGaAlAs lower side light
guide layer 104 having a thickness of 0.05 micrometers;

5   a well layer of 1% compression distorted InGaAlAs
(growth wavelength 1.37 micrometers) having a thickness
of 6.0 nm; a 10-cycle multi-well layer 105 formed from
In GaAlAs (growth speed 1.00 micrometers) isolation
layer having a thickness of 10 nm; an upper side light

10   guide layer 106 having a thickness of 0.05 micrometers;
a p-type InAlAs clad layer 107 having a thickness of
0.1 micrometers; a p-type InP clad layer 108 having a
thickness of 0.15 micrometers; and a high-concentration
p-type InGaAs cap layer having a thickness of 0.2

15   micrometers. The multi-quantum well active layer 105
have light emitting wavelength of about 1.31
micrometers.

      Next, by using a stripe-shaped guide mask and
the known selective dry etching technique, a ridge

20   waveguide is formed. Here, as shown in Fig. 1, in
addition to a straight-line-formed mono lateral mode
waveguide 113 having a width of 1.6 micrometers, a
multi-mode interference waveguide 114 is formed in such
a manner that the lateral width is increased at the

25   center portion of the waveguide. By properly designing
the lateral width W_{mmi} and the waveguide length L_{mmi}, it
is possible to obtain a high optical connection between
the mono-mode waveguide and the multi-mode interference

waveguide. Here, considering the theoretically optimal approximate value ($L_{mmi} = nW_{mmi}^2/\lambda$, wherein n is a waveguide effective refraction index and λ is an operation wavelength), the lateral width was set to 6.0

5 micrometers and the length was set to 89.7 micrometers. Because of the manufacturing error, it is difficult to completely satisfy $L_{mmi} = nW_{mmi}^2/\lambda$ but an error of ±10% is normally allowed. Moreover, when considering that the lateral width W_{mmi} of the multi-mode waveguide has a

10 lower limit of about 3 micrometers and accordingly, n is assumed to be about 3.2, the L_{mmi} has a lower limit of about 18 micrometers in case the wavelength is 1.55 micrometers. After this, the known ridge waveguide laser structure was subjected to wafer processing.

15 After cutting into the element length 100 micrometers, on the front surface of the element was formed a high-reflection film 111 having a reflection factor of 80% and on the rear surface was formed a high-reflection film having a reflection factor of 97%. As shown in

20 Fig. 1, a conventional element 113 entirely consisting of a straight waveguide is formed on the same substrate as a reference.

Fig. 2 shows a similar embodiment. This embodiment differs from the embodiment of Fig. 1 in

25 that the reflection surface of laser back was prepared by using the known dry etching technique. In this case, the laser resonator length can be reduced further down to 50 micrometers or less as compared to the

embodiment of Fig. 1.

Fig. 3 shows a modification of the embodiment of Fig. 2, in which the laser back reflection mirror is replaced by the known distribution reflection mirror

5 115 consisting of semiconductor/air and a light output monitor 116 is monolythically integrated.

Fig. 4 shows check results of the laser element current/light output characteristics of the laser element shown in Fig. 2 under the 85°C and CW

10 conditions. As shown in the figure, in the conventional type straight waveguide laser, the light output was thermally saturated at a low current level of about 42 mA. The main cause of this was a high electric resistance. On Fig. 4, current dependency of electric

15 resistance is plotted. As is clear from this plot, in the straight waveguide element, when the resonator is reduced to 50 micrometers, the resistance becomes as high as 40 ohms or above. Because of this output saturation, it becomes impossible to obtain a desired

20 light output. Furthermore, as is clear from the current dependency of the mitigation oscillation frequency shown in Fig. 5, saturation occurs at the level of 26 GHz and it is impossible to realize a high-speed direct modulation such as 40 giga bits per

25 second. As compared to this, in the laser using the multi-mode interference waveguide, the electric resistance is reduced to 20 ohms which is about half of the aforementioned value. This is the effect of that the

current flow area is increased by introducing the
multi-mode interference waveguide. This improves the
saturation light output of Fig. 4 by about twice as
compared to the conventional element. Moreover, the
5   mitigation oscillation frequency can be increased to 45
GHz, thereby enabling a high-speed direct modulation of
40 giga bits per second. The present invention is
further characterized in that the threshold value
current density can be reduced. In the conventional
10   element, if the resonator length is reduced to improve
the high laser speed, the active volume is reduced and
the threshold value carrier density is remarkably
increased. For this, as shown in the gain-carrier
relationship of Fig. 6, laser operates in the gain
15   saturation region. This not only lower the differen-
tial gain but also increases non-linear type damping.
As a result, both of these effects deteriorate the
laser high speed. According to the present invention,
the problem of increase of the threshold value current
20   density can be solved. That is, it is possible to
reduce the threshold value current density of the short
resonator laser and accordingly, it is possible to
simultaneously increase the mitigation oscillation
frequency and suppress damping. Thus, it is possible
25   to improve the laser high speed characteristic by a
simple method.

        Thus far has been explained a typical embodi-
ment of the present invention using the ridge waveguide

type laser structure formed from InGaAlAs material.
The present invention can be applied to all the semi-
conductor materials such as InGaAsP, GaInNAs, InGaAs,
InGaAlP, and the like. Moreover, the present invention

5 can be applied not only to the ridge waveguide type
laser but also to a laser having a so-called embedded
hetero-structure and a embedded ridge structure.

[Embodiment 2]

Fig. 7 shows a 1.55-micrometer band distribu-

10 tion reflection type laser capable of changing an
oscillation wavelength by an electric signal according
to the present invention. The continuous wavelength
change characteristic of the distribution reflection
type laser is determined by the laser longitudinal mode

15 jump. The laser longitudinal mode jump interval $\Delta\lambda_{DBR}$
depends on the active region length L_a and is defined as
follows:

$$\Delta\lambda_{DBR} = \lambda^2/2nL_a \qquad\qquad (1)$$

wherein λ is an oscillation wavelength and n is an

20 optical refractive index of the laser medium. Accord-
ingly, in order to enlarge the continuous wavelength
change width, at least $\Delta\lambda_{DBR}$ should be increased. When
the wavelength band λ is fixed, as is clear from
Equation (1), in order to increase the $\Delta\lambda_{DBR}$, the only

25 effective means is reduction of L_a. In the second
embodiment, like in the first embodiment, the laser
characteristic deterioration such as the electric
resistance increase and output lowering upon reduction

of L_a can be improved by introducing the multi-mode
waveguide into the active region.

In Figs. 7A and 7B, on the n-type (100) InP
semiconductor substrate 501 are successively formed by
the organic metal gaseous phase growth method: an n-
type InGaAlAs refractive index control layer (composi-
tion wavelength 1.40 micrometers) having a thickness of
0.3 micrometers; an InAlAs etching stop layer having a
thickness of 0.02 micrometers; a p-type InP spacer
layer having a thickness of 0.02 micrometers; and an
InGaAsP (composition wavelength 1.37 micrometers)
diffraction grating supply layer 504. Next, 241-nm-
cycle uniform diffraction grating is printed onto the
diffraction grating supply layer 504 by the known
method. Subsequently, by using the known selective
etching and the known technique for directly connecting
a waveguide of a different type, 5-cycle multi-quantum
well layer 502 is formed from a distorted InGaAlAs
material only at a portion to become an active region
of the distribution reflection laser. Subsequently, a
p-type InP clad layer 505 having a thickness of 1.5
micrometers and a high-concentration p-type InGaAs cap
layer having a thickness of 0.2 micrometers are succes-
sively formed by the organic metal gaseous phase growth
method. The multi-quantum well active layer 502 has a
light emitting wavelength of about 1.56 micrometers.

Next, by using a stripe-shaped mask and the
known selective dry etching technique, a ridge wave-

guide is formed. Here, a mono-lateral mode waveguide of strait line shape having a width of 1.6 micrometers is formed on the regions which are to become a distribution reflector and a phase adjusting area and a

5   part of the active region. Furthermore, a multi-mode interference waveguide whose center portion has a greater width than the other portion is formed at the center portion of the active region. By designing the lateral width of this multi-mode waveguide and the

10 length of the waveguide to be appropriate values, it is possible to realize a high optical connection between the mono-mode waveguide and the multi-mode interference waveguide. Here, the width was set to 6.0 micrometers and 74.6 micrometers. The distribution reflector, the

15 phase adjusting region, and the active region have length of 250 micrometers, 80 micrometers, and 100 micrometers, respectively. An isolation region of 25 micrometers was provided between the respective regions. The entire element length was 480 microm-

20 eters. The wafer after the growth was subjected to wafer processing to have the known ridge waveguide laser structure and cut into the element length of 480 micrometers. After this, the element front surface was covered by a low reflection film 510 having a reflec-

25 tion factor of 0.1% while the element back surface was covered by a high reflection film having a reflection factor of 95%.

The distribution reflection type laser thus

prepared had mono-axis mode oscillation in the 1,550 nm

band.   The threshold value current was 10 mA.   The chip

light output at laser current of 60 mA was about 10 mW,

which is sufficient for optical communication.   While

5   keeping the laser current to be 60 mA, current was

applied to the distribution reflector, thereby tuning

the oscillation wavelength.   The wavelength change

characteristic is shown in Fig. 8B.   In contrast to

this, Fig. 8A shows the wavelength tuning character-

10   istic of a conventional distribution reflection type

laser in which the total of the active region and the

phase adjusting region is 410 micrometers.   Longitu-

dinal mode jump can be seen at wavelength interval of

about 0.8 nm corresponding to 410 micrometers.   This

15   longitudinal mode jump is accompanied by a sub-mode

suppression ratio greatly changing.   On the other hand,

in the element of the present invention, the longitu-

dinal mode jump wavelength interval is increased to 1.6

nm and the control current interval where the longitu-

20   dinal mode jump occurs is increased.   This is because

the total length of the active region and the phase

adjusting region has been reduced to 205 micrometers,

which is a significant improvement from the viewpoint

of realizing the continuous wavelength tuning not

25   causing mode jump.   On the other hand, when assuming 40

dB as the mono longitudinal mode reference, in the

element of the present invention, mono longitudinal

mode operation of 40 dB and above is realized in a

wider control current range as compared to the conventional element. It should be noted that setting of the oscillation wavelength at the wavelength between the longitudinal mode jumping is easier than adjusting the

5 current to be applied to the phase adjusting region.

Thus, by introducing the multi-mode interference waveguide into the active region of the distribution reflection type laser, it is possible to obtain a sufficient light output while maintaining the

10 spectrum unity upon wavelength change.

[Embodiment 3]

Figs. 9A and 9B show a third embodiment. The third embodiment is different from the second embodiment in that the active region is reduced to 33

15 micrometers and the continuous wavelength change region is enlarged. In this case, it is possible to continuously change wavelength by several nm without using the phase adjusting region. The basic structure and production method of the third embodiment is identical

20 to the second embodiment except for that no phase adjusting region is provided and that the semiconductor light amplifier for increasing light output is monolythically integrated. The main difference in the laser design is that the diffraction grating has an

25 optical coupling coefficient increased to 200 cm^{-1} so as to compensate the laser gain lowering due to reduction of the active region and that the diffraction grating phase at the front and back regions of the active layer

is reversed to obtain a stable mono-axis mode oscilla-

tion in the vicinity of the Bragg wavelength, thereby

obtaining a so-called $\lambda/4$ shift type.

      In the laser of the present invention, the

5   continuous wavelength change width of 4 nm and the

light amplifier output of 10 mV were easily obtained.

In this embodiment, since the active region is short,

the optical phase change in the active region due to

wavelength change is very small. As a result, the

10   longitudinal mode jump cannot be easily caused, which

is the important point of the present invention. By

introducing the multi-mode interference waveguide, it

is possible to suppress an abrupt increase of the

electric resistance, which is the essential point of

15   the present invention.

[Embodiment 4]

      Fig. 10 shows a fourth embodiment of the

present invention. The fourth embodiment is different

from the third embodiment in that a field absorption

20   type optical modulator 736 and a power monitor 735 are

monolythically integrated. In this case, in addition

to the wide range continuous wavelength change

characteristic, it is possible to realize a low-chirp

high-speed modulation and to provide a light source

25   especially preferable for a high-density wavelength

multi-optical transmission.

      The advantage obtained by introducing the

multi-mode interference waveguide has been thus far

explained by using the Embodiments 2 to 4. This effect can also be applied to a similar improved distribution reflection type laser using a sample diffraction grating structure, a super structure diffraction grating structure, and the like.

By using the semiconductor light emitting element according to the embodiments of the present invention, it is possible to realize direct modulation of 40 giga or above per second. It is also possible to reduce the cost of the optical components, to reduce the cost of the optical communication system using this element, and to realize a large capacity. Moreover, the present invention provides quite a simple method for producing a wavelength change distribution reflection type semiconductor laser operating with a stable mono-mode and high output as well as an optical module using the same. By using the embodiments of the present invention, it is possible not only to significantly enhance the element performance and production yield but also to improve the optical communication system using the element in cost, capacity, and distance.

It should be further understood by those skilled in the art that the foregoing description has been made on embodiments of the invention and that various changes and modifications may be made in the invention without departing from the spirit of the invention and the scope of the appended claims.